

The RoboCup Nanogram League: An Opportunity for Problem-Based Undergraduate Education in Microsystems

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Abstract—A problem-based learning approach was chosen for a new senior elective in microsystems. The problem posed to the students was to design microrobots suitable for the new “nanogram league” of the international RoboCup competition, which challenges teams of students and researchers to construct microscopic untethered robots that will compete against each other in soccer-related agility drills on a 2.5mm by 2.5mm playing field. The approach was shown to increase student interest and motivation. The course was considered a success, and will be repeated with some modifications to increase the breadth of the course coverage.

Index Terms— Microelectromechanical devices, problem-based learning, micro-robotics, scratch drive actuators, undergraduate education, student competitions

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I. INTRODUCTION

An undergraduate course in the field of microelectromechanical systems (MEMS), also called “microsystems,” presented unique educational challenges [1]. In many ways, the material taught was more accessible to undergraduates than that presented in semiconductor device courses – the devices move and interact with the environment in a way the students can readily witness, and the material is application-driven. But the material was also inherently multidisciplinary. To understand microsystems requires a working knowledge of many subjects. How can all of these topics be combined to form a course with cohesion and depth?

A problem-based approach provided a framework that connected seemingly disparate subjects into a cohesive story. In problem-based learning, students work in groups to solve a challenging problem. The students decide how to approach the problem, while the role of the teacher is to guide and advise. The problem dictates what subjects the students will investigate and to what depth. In this respect, problem-based learning is closer to engineering practice than is the traditional “bottom-up” teaching approach. Problem-based learning has been shown to boost information retention, and communication and group skills, although there is mixed data on how it affects performance on standardized tests covering fundamentals [2]-[5]. Problem-based learning has also been applied in a number of undergraduate engineering programs, where it was found to increase student interest and motivation [6]-[8].

The challenge for the educator when formulating a problem-based course is to determine a suitable problem that will engage the students, provide sufficient complexity, and yet be manageable within the time scale of the academic year. A

course on microsystems at the United States Naval Academy used a robotics competition, RoboCup [9]. The new “nanogram league” of the competition challenged teams of students and researchers to construct microscopic untethered robots to compete in soccer-related agility drills. This competition created many multidisciplinary educational opportunities in microsystems as well as in the area of vision-based robotic control.

II. EDUCATIONAL OBJECTIVES

The course that inspired participation in Robocup was a fall, senior-year elective on microsystems offered by the Electrical Engineering Department at the United States Naval Academy. Senior elective class sizes were typically small (less than ten). The microsystems course was first offered in the fall of the 2006-2007 academic year as an experimental course and had an enrollment of three students. The objectives are shown in Table I below. The students were all electrical engineering majors and had no exposure to the fundamental mechanical engineering subjects of statics, dynamics or material science. The only previous exposure of the students to microsystems was in their junior-year electronics course, where the principles of semiconductor devices and the silicon chip manufacturing process were introduced in broad terms.

Table I. Learning Objectives for Microsystems Course

A student completing the microsystems course should be able to...	
Objective 1	Describe the field of microsystems and its largest contributions to military and civilian needs.
Objective 2	Describe standard microfabrication techniques.
Objective 3	Describe common actuation and sensing methods in microsystems.
Objective 4	Calculate voltages and currents for electrostatic and thermal actuators and sensors given geometry and material property information.
Objective 5	Analyze a given microsystem to explain its operation mechanism and how it is manufactured.
Objective 6	Determine a process sequence using standard microfabrication techniques that will result in a desired device design.
Objective 7	Design and layout a device using a commercial fabrication sequence.
Objective 8	Apply microfabrication techniques in the laboratory
Objective 9	Test and evaluate a microsystem design and make suggestions for improvement
Objective 10	Communicate his or her work using appropriate technical writing format and including proper citations to previous work.

A problem-based learning structure was sought because of the desire to combine breadth (objectives 1-3) with depth (objectives 4-8) within the course. A microrobotics-

based problem has many characteristics that suit it to meet this need. First, robots are interesting to students and exciting to test and observe. Second, microscale robotics systems are the subject of much current research, making them a “hot” topic [10]. Third, microrobots can be made by combining standard MEMS processes with simple microfabrication steps that the students could perform themselves in the laboratory. Finally, an exploration of microrobotics requires particular depth in the understanding of electrostatic actuation, which is the most common actuation mechanism for microsystems. The students at the Naval Academy also respond particularly well to competition. Thus, the new nanogram league of the international Robocup tournament provided an excellent focus for the course.

III. THE PROBLEM

The demonstration competition held at the Georgia Institute of Technology in July 2007 consisted of three compulsory events: a 2 millimeter dash, a slalom drill, and a ball-handling drill. The playing field has a layer of interdigitated electrodes, coated by a thin insulating layer. Defenders consisted of photoresist patterned at various points on the field of play, and thin-film discs of silicon nitride served as balls. Each player must fit within a bounding box measuring 300 micrometers on a side and must be capable of operation on the playing field without the presence of any physically connected wires or tethers. The robots must be controlled by a voltage waveform applied to the underlying electrode array on the playing field.

The inspiration for the competition, illustrated in Fig. 1, is a microrobot built by Donald *et al.* at Dartmouth [11], [12]. The Dartmouth microrobots were 60 μm by 250

μm by $10 \mu\text{m}$. Forward motion was accomplished via scratch drive actuation, described in [11] and illustrated in Fig. 2. Turning was accomplished by bringing the arm down in contact with the substrate while stepping the robot forward, so that the robot moved in an arc about the stylus.

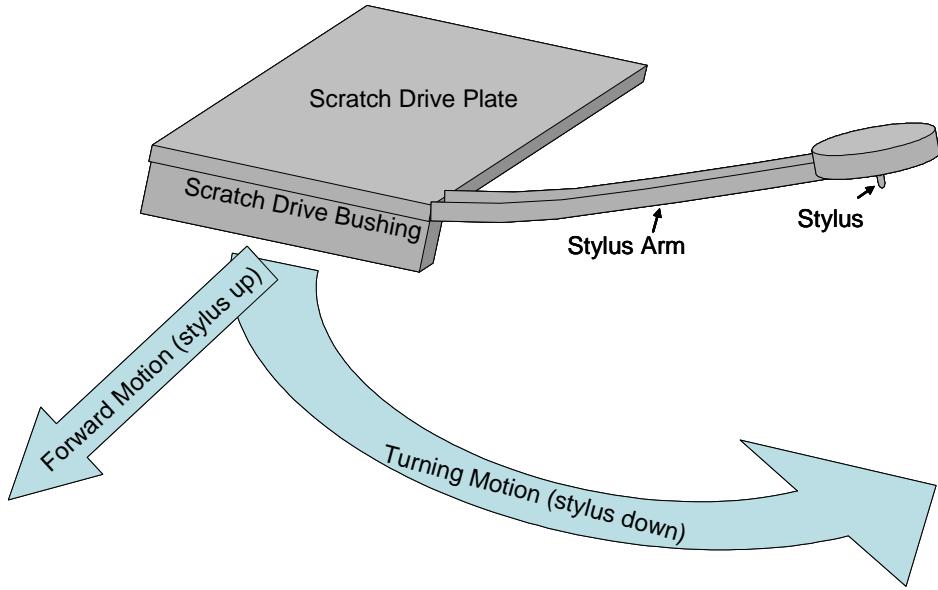


Fig. 1. Illustration of microrobot

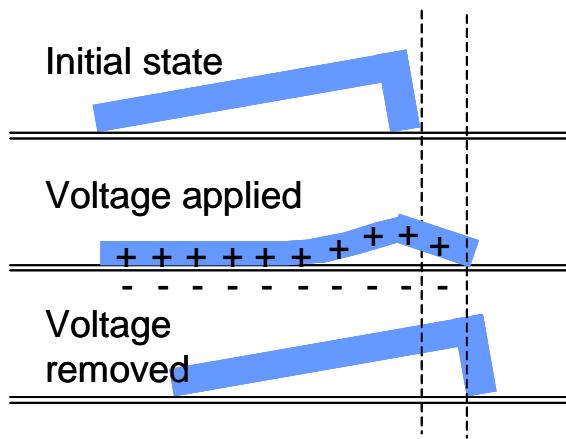


Fig. 2. Illustration of scratch drive operation

The actuation voltages for the scratch drive, and for bringing down and releasing the stylus arm, were critical to the operation of this device. The pull-down and release voltages for the scratch drive must be nested within the pull-down and release voltages for the stylus arm. Thus, one appealing aspect of this robot design was that the students must understand electrostatic actuation and be able to calculate pull-in and release voltages in order to design such robots. Examples of the waveforms for moving straight and for turning are shown in Fig. 3.

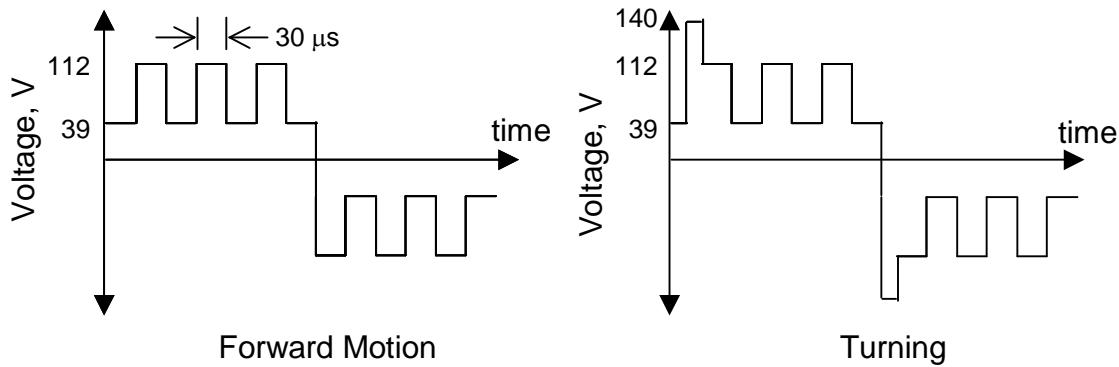


Fig. 3. Illustration of robot control waveform. For forward motion, the signal flexes the scratch drive plate, periodically changing voltage polarity to avoid charging. For turning, the signal first pulls down the stylus with a higher voltage before flexing the scratch drive.

The Dartmouth microrobots were built using a surface micromachining process that combined a commercial fabrication process (PolyMUMPS [13]) with a handful of additional process steps, in order to deposit a thin layer of tensile material on the turning arm. This final step was critical in setting the stylus pull-down voltage. Hence another pedagogical advantage of this problem is that it required the students to work through a commercial process—learning CAD tools and the application of design rules—but also provided an opportunity for hands-on exposure to photolithography, metal deposition and etching.

The post-processing requirements could be met by a small and modestly equipped microfabrication laboratory, requiring only metal deposition equipment, a contact aligner, and a wet bench stocked with standard microfabrication chemicals. Furthermore, the masks required for post-processing the devices had large enough feature sizes that inexpensive transparency masks could be used. For testing, the problem required a probe station equipped with a digital camera, a function generator, an oscilloscope, a high-voltage amplifier, and a laptop for programming the waveform and for implementing automated control of the robots.

IV. PEDAGOGICAL APPROACH

In keeping with the principles of problem-based learning [2], the students had the responsibility for setting the syllabus in the microsystems course. The instructor presented the Dartmouth microrobot as a starting point for student work. After reading the RoboCup problem statement and technical papers on the Dartmouth microrobots [11], [12], the students determined which topics they would need to study, and set an aggressive schedule that was largely constrained by the deadlines and two-month turn-around time for the PolyMUMPS process. In order to provide a broader perspective on microsystems as a whole, the instructor also assigned weekly homework based on readings from a text surveying the field of microsystems [14], as well as selections from other texts [15], [16] and several microsystems papers [17]-[22]. The syllabus and reading schedule for the course are shown in Table II.

Table II: Syllabus set by students for Microsystems Course

WEEK	READING	CLASS ACTIVITY
1	CMOS Review	Course and project introduction
2	MEMS and materials overview	Review of prior work and derivation of design equations
3		L-EDIT training and PolyMUMPS Layout
4		
5	MEMS process tools	
6	Sensing and Actuation Methods Survey	Microfabrication training, process development, and construction of testing apparatus
7	Passive mechanical structures	
8	Actuators	
9		
10	Photonic Microsystems	Device post-processing
11	BioMEMS	
12	RF MEMS	
13	Packaging and Reliability	
14		
15		Microrobot testing and final report preparation
16		

After reviewing fabrication techniques, the students went on to study actuation methods, focusing on electrostatic actuation. They derived the design equations for the scratch drive actuator and the pull-in and release voltages for the stylus arm, and checked their calculations against the published voltages for the Dartmouth microrobots. They then learned the layout software, and designed structures for the first PolyMUMPS run: a combination of test structures, devices identical to the Dartmouth robots, and robots with key geometric parameters altered to test their understanding of the design equations.

As in the Dartmouth microrobot, the student design combined commercial processing with one additional photolithography layer. Most of the robot structure was created in the commercial process, however a final metal layer was added after the commercial

process in order to elevate the stylus arm and appropriately nest the control voltages. The material choice, deposition conditions and thickness for this final layer were critical design parameters. The students were particularly encouraged to explore these parameters, both in calculations and in the laboratory.

The students also designed and built the test apparatus for the microrobots, including a vacuum microprobe to manipulate the microrobots on the probe station and adaptations to the probe station that allowed for humidity control of the environment, which was critical to microrobot operation (Fig. 4).

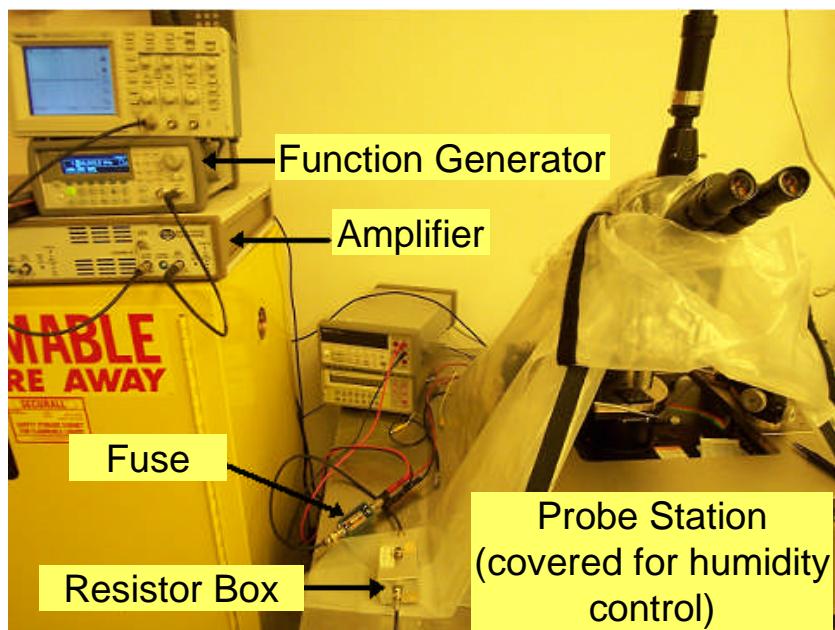


Fig. 4. Test station for microrobots developed by students in microsystems course

A few implementation problems were encountered: test playing fields from the contest organizers were not yet available, alignment for the lithography process was more difficult than anticipated on the small die, the humidity was too high even with the initial control measures, and static charge interfered with the performance of the microprobe. However, by the end of the semester the students demonstrated forward

motion with tethered microrobots, and had developed the process for depositing metal on the stylus arms. In addition to demonstrating device performance, the students prepared a report at the end of the semester describing their work on the project. A scanning electron micrograph of a robot made by the students is shown in Fig. 5.

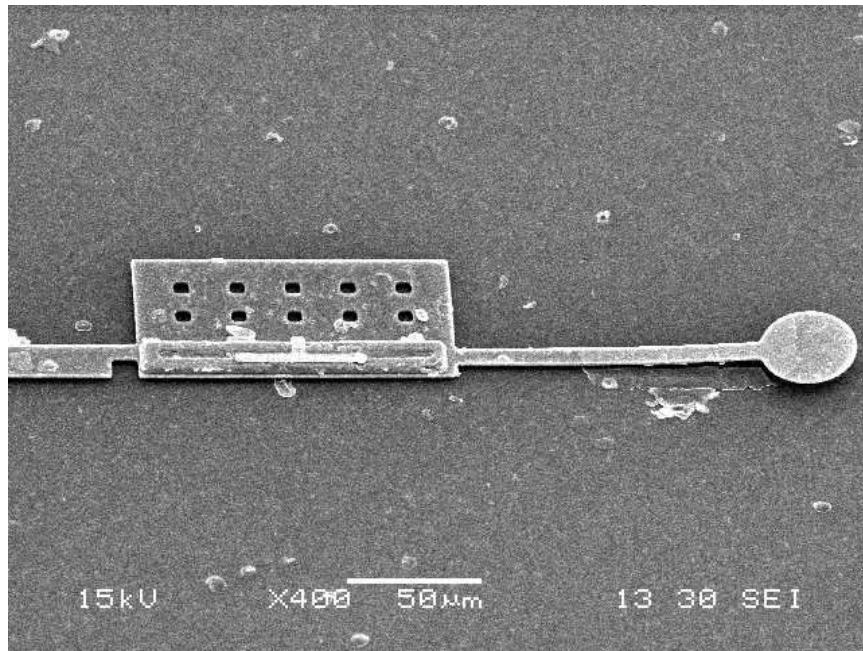


Fig. 5. Scanning electron micrograph of completed robot (still attached to substrate tether)

The final student design was very similar to the Dartmouth design, but the students demonstrated critical thought in their exploration of design alternatives, including variations in the post-processing layer thickness and dimensions, variations in the stylus dimensions, the addition of ball handling extensions, and an attempt to add a second stylus arm for bidirectional turning (Fig. 6).

The project and the problem-based learning approach exposed the students to more than microsystems. The students were also exposed to project management in setting up their work timetable and monitoring their progress, and they used library resources to locate journal articles and material properties. Two of the students from the

microsystems course went on to train two other seniors in the spring semester who joined the team as it prepared for competition.

A further advantage of the Robocup problem was that it provided an opportunity for multidisciplinary teaming in follow-on work. In addition to the task of designing and building the robots themselves, the problem also presented machine vision and automated control issues. The machine vision and control issues were addressed separately by coursework and independent study in the Systems Engineering department. Students from both courses then came together in a multidisciplinary team as a senior capstone project in the spring semester, where the microrobot system was improved and prepared for competition.

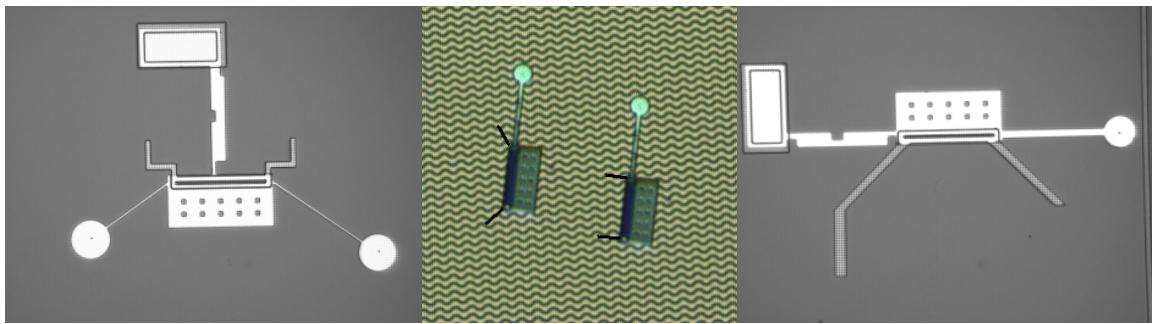


Fig. 6. Design alternatives explored by students

By the end of the academic year, the students were able to demonstrate forward, untethered motion using robots whose arms were removed, but they were still having difficulty with the turning motion primitive (Fig. 7). This problem was caused by continued difficulties with the post-processing, resulting in the turning arm being elevated to the extent that its pull-in voltage exceeded the pull-in voltage of the scratch drive. The fabrication issues also prevented the students from further exploring their design alternatives.

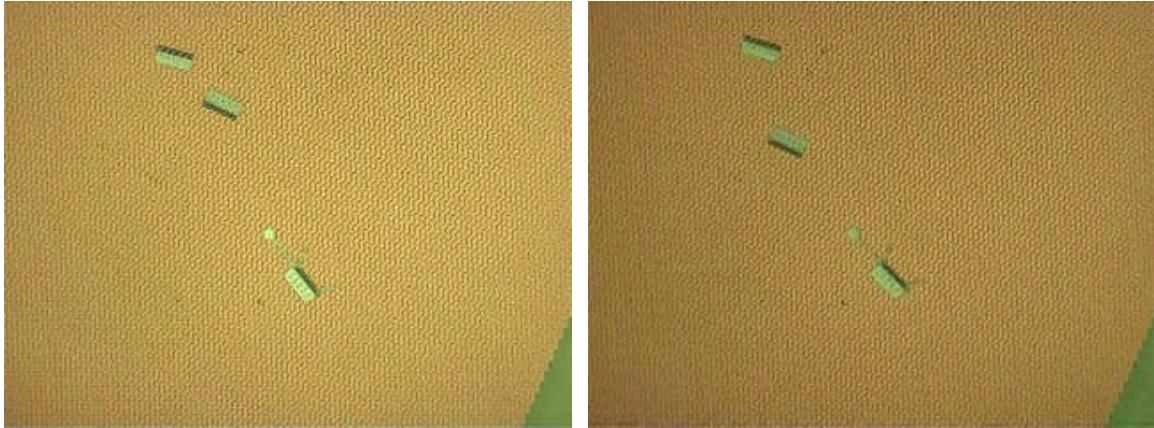


Fig. 7. Images taken at two points in time for microrobots in motion. Notice how the two robots in the upper left corner are moving apart while the robot in the lower right has rotated only slightly before sticking in place.

Fortunately, some of the team members were able to continue to work on the problem between graduation and the competition, and improved the post-process to achieve devices with sufficiently elevated arms. Both straight and turning motion was demonstrated with these devices. The devices were taken to competition in early July, where the Naval Academy was the only all-undergraduate institution to participate. The midshipmen were able to compete in every event, and their success contributed significantly to the decision of the RoboCup governing board to continue the new league.

V. ASSESSMENT

The students were evaluated through problem sets based on the reading assignments for the week and on a final report detailing their work with the microrobotics project. The course was evaluated using the instructor's judgment as to how the course met the learning objectives, a student survey at the end of the course, and a cross-course comparison survey done at the end of the year. The result of the

instructor's evaluation is shown in Table III. The instructor found that the students showed mastery of the objectives as they related to the microrobots but did not display the desired breadth in extending that mastery to the analysis of alternate microsystems. This finding may be a fault of the course structure, where the breadth of microsystems was covered only in reading assignments done outside of class.

Table III. Evaluation of Accomplishment of Learning Objectives for Microsystems Course

	Objective	Grade	Comment
1	Describe the field of microsystems and its largest contributions to military and civilian needs.	C	Covered in homework assignments and not reinforced through quizzes or tests.
2	Describe standard microfabrication techniques.	A	In their evaluation of the initial microrobot design and ways to improve the process, students revealed a thorough understanding of microfabrication techniques.
3	Describe common actuation and sensing methods in microsystems.	B	
4	Calculate voltages and currents for electrostatic and thermal actuators and sensors given geometry and material property information.	B	The students met all of these objectives for the microrobot, but did not demonstrate the same mastery in homework assignments that required analysis and design of other microsystems.
5	Analyze a given microsystem to explain its operation mechanism and how it is manufactured.	B	
6	Determine a process sequence using standard microfabrication techniques that will result in a desired device design.	B	
7	Design and layout a device design using a commercial fabrication sequence.	A	The students mastery of these skills was sufficient to train the new team members in the senior design course.
8	Apply microfabrication techniques in the laboratory	A	
9	Test and evaluate a microsystem design and make suggestions for improvement	A	Students were able to evaluate the initial microrobot design and make suggestions for improvements.
10	Communicate his or her work using appropriate technical writing format and including proper citations to previous work.	A	Reports were very well written and included proper reference to prior work.

Student feedback taken from anonymous surveys given at the end of the fall semester was also examined. The course did very well in the student surveys, with all three students rating the course as “one of the best” technical courses they had taken at the Academy. The students in particular cited “working in the lab” and “actually making something” as the strongest features of the course. The only suggestion for improvement, which was made by all the students, was to change the structure of the course from the traditional three single-hour sessions and one double-hour session per week to a course with one single-hour session and two double-hour sessions per week.

To obtain more information, the students from the microsystems course were surveyed again at the end of the spring semester. This time, identical surveys were given to students in two other senior electives: one of which was purely a lecture course with an enrollment of three, and the other a more traditional lecture and laboratory course with an enrollment of five. Both of the additional courses were offered in the spring.

The survey for each course consisted of only five statements, to which the students were asked to indicate their level of agreement:

1. I can describe the field of [field covered by class] and can comprehend and analyze a particular [sample system or device].
2. I can design a [sample system or device] to meet a specified need.
3. I can evaluate a [sample system or device] and make suggestions for improvements.
4. I know what resources I could use to learn more about this field.

5. This course has increased my interest in engineering and technology.

The results were then correlated to a numeric scale with 5 equal to “strongly agree” and 1 equal to “strongly disagree” and compared across courses, as is shown in Fig. 8. In this survey, the microsystems course rankings were similar to that of the other courses, except in the area of design, where the microsystems course ranked well below the traditional lab/lecture course. With such small enrollments, the data is inconclusive, but this supports the instructor’s observation that the students’ knowledge of design did not extend beyond microrobots to other microsystems.

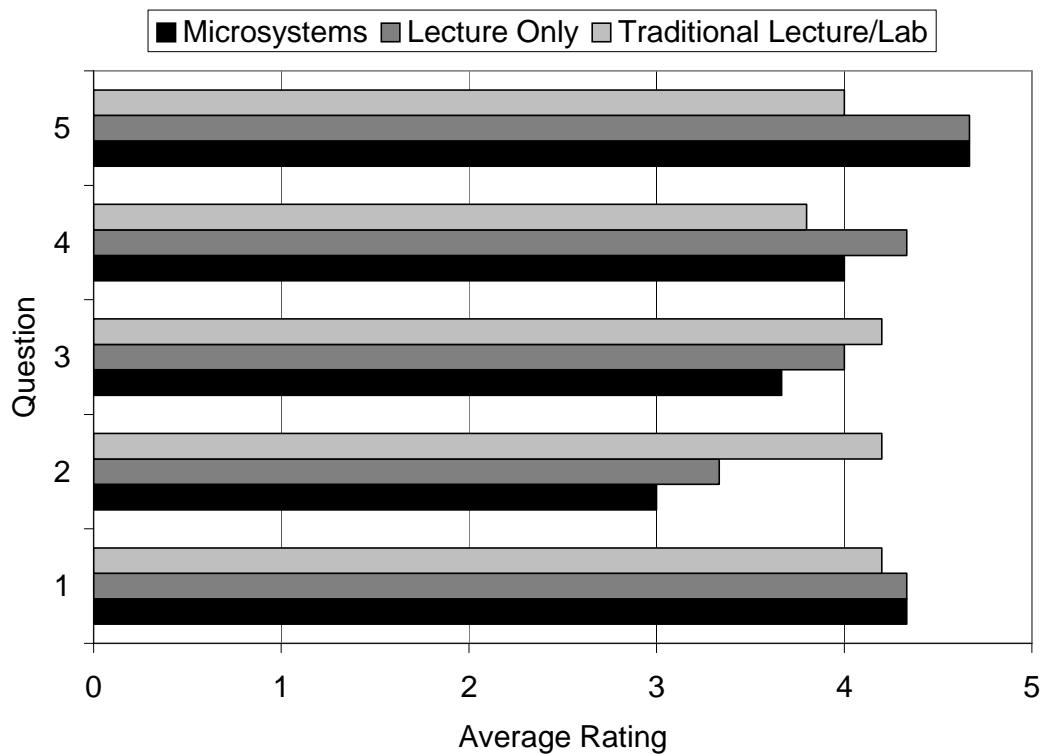


Fig. 8. Comparison of student responses in cross-course surveys.

Overall, the assessment results were mixed. The course did engage the students and was successful in teaching a deep understanding of microrobotics, but not as successful in teaching the breadth of microsystems. To address this issue in future

offerings, the course should be structured with one “lecture” period and two “lab” periods. The microrobotics problem should be addressed during the lab periods, while the lecture period should be focused on other microsystems and use in-class design exercises and other active techniques in addition to reading assignments. Quizzes should also be used to reinforce this material.

VI. SUMMARY

A problem-based learning approach was adopted for a senior electrical engineering elective in microsystems. The problem chosen was to design microrobots to compete in the new Nanogram League of the RoboCup competition. The students enjoyed the project, and were able to demonstrate fully functional robots by the end of the academic year. Assessment of the microsystems course revealed that while the course was successful in conveying depth in the topic of microrobotics, it did not convey sufficient breadth. The course will be modified in future offerings to address this issue, but will continue to use a problem-based learning approach with a focus on microrobotics.

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